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Estimation of Magnetic Properties of Tissue with Magnetic Fluid by SV-GMR Needle Type Probe

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The main aim of this article is to present the possibility to estimate the content density of magnetic fluid in various shape cavities by SV-GMR needle type probe. Changes caused by the shape and amount of ferrite included in cavity were examined. Analytical model and numerical calculation were performed to confirm these results. We assume that if the signal changes are linearly dependent on magnetic permeability of sample and with known shape ratio it is possible to estimate the amount of the iron consisted in the sample.

Key Words: GMR sensor, Demagnetizing factor, Magnetic nanoparticles, Lee Whiting coil.

1. Introduction

Almost all living organisms utilize trace amount of iron in the metabolism processes. This element can be found in various oxidation states, can form chemical compounds, and can be in different physical states. Hence, the biological substances that include it are characterized by various magnetic properties.

During the hyperthermia treatment the magnetic fluid is injected directly into the cancer cells. Magnetic fluid consisting of nanoparticles can be used as a heating agent causing apoptosis of cancer cells [1]. Weight density of the magnetic fluid is a crucial parameter to apply proper heating during hyperthermia treatment. The concentration of magnetic fluid was investigated in the previous work [1]. Although, that time the research was not focused on the influence of various sizes and shapes of the estimated cavity and the changes of the magnetic flux density inside was not considered. This paper presents results of the experiments addressing both mentioned problems. It is well known that the uniform magnetic field H_0 causes the changes of the magnetic force H inside a material of irregular shape [2]. In order to obtain the information about these changes the studies on the dependence of magnetization J on magnetic force are essential to estimate the directional parameters of the examined material [2]. Therefore, the theoretical calculations of the changes of H in different direction in various shapes were performed [2-4]. Having the knowledge about the changes of the magnetic field in regard to the object shape and the amount of the magnetic substance (consisting of iron particles) in the object allows estimating the contents of iron in the sample.

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2. Analytical and Numerical Model

2.1 Analytical model

When the uniform external magnetic flux density B_0 is applied to magnetic fluid in the specific embedded cavity (Fig. 1.) the magnetic flux lines converge at the cavity within the magnetic fluid. Therefore, the magnetic flux density B at the center of the cavity can be expressed as:

$$B = (\mu_r * B_0)/[1 + N(\mu_r - 1)] \tag{1}$$

where N is the demagnetizing factor of cavity [2-4], μ_r is the relative permeability of the sample, which is slightly greater than one. With this assumption it is possible to derive equation:

$$(B - B_0)/B_0 \cong (1 - N)(\mu_r - 1) \tag{2}$$

In numerical calculations magnetic nanoparticles are assumed to have a cylindrical shape with equal height and diameter. They are uniformly distributed in the fluid and have a relative permeability of infinity compared to that of one for liquid. Hence, the permeance of equivalent magnetic path through magnetic bead and through air is estimated as:

$$\mu_r = 1 + C_d D_w / h_s \gamma_f \tag{3}$$

where C_d is coefficient theoretically = 3-4 [1]; $D_w << 1$ – magnetic fluid weight density; $h_s = 0.523$ – spherical factor of magnetic fluid; $\gamma_f = 4.58$ – specific gravity of fluid.

The magnetization of the diluted samples was tested by vibrating sample magnetometer to confirm (3). Results of magnetization obtained from the VSM are presented on Fig. 2. The experimental and theoretical calculation of weight density and relative permeability are presented in Fig. 2 right bottom rectangle. It can be easily noticed that sample magnetization in the measured field ±600 A/m is linear (Fig. 2 left top rectangle). Experimental and theoretical calculation results presented in Fig. 2 are in good agreement. From Eq. (3) it can be seen that the relative permeability is proportional to the magnetic fluid weight density. And the change ratio δ between the magnetic flux B and B_0 is:

$$\delta = (B - B_0)/B_0 = [(1-N)C_d D_w]/\gamma_f \qquad (4)$$

It is possible to estimate the magnetic properties of tissue with the magnetic fluid when the change of the ratio δ is measured and the dependence of the relative permeability on weight density of fluid and the shape ratio of a cavity is known. It is worth to mention that the percentage changes are very small what imposes the utilization of a particular, very sensitive experimental setup.

2.2 Finite element method analysis

In order to confirm the experimental results the 3D model of the Lee Whiting coil and sample under examination were prepared. Simulation was performed in Comsol Femlab AC/DC module. Lee Whiting coil produced uniform magnetic field B_0 equal to 700 μT around the sample. A cavity with the magnetic fluid caused that the magnetic flux density in the center of the sample increased to B. The difference between the magnetic flux density B, inside the middle of the sample, and the magnetic flux density B_0, two centimetres above the sample, was calculated. The theoretical influence of the magnetic flux changes caused by a cylindrical container of a specified shape ratio (height/diameter = 0.5, 1.0, or 2) filled by different concentration of magnetic fluid (D_w= 0.02, 0.4, 0.8 %) are presented in Table 1. The change of the magnetic flux is very small in comparison with the applied magnetic flux density. Theoretical calculations show that the changes are within μT's range, which are measurable by the SV-GMR needle type sensor.

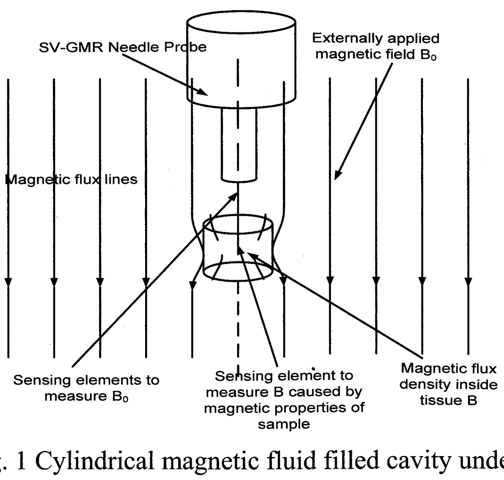

Fig. 1 Cylindrical magnetic fluid filled cavity under the influence of a uniform magnetic flux density.

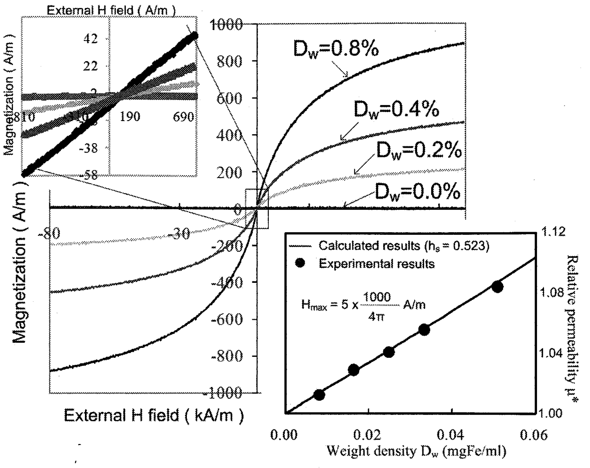

Fig. 2 Sample magnetization VSM results.

Table 1 Numerical calculation results $B-B_0$ in (μT).

Weight density	height/diameter (mm)		
D_w(%)	3/6	6/6	12/6
0.21	1.06	1.73	2.20
0.41	2.04	3.30	4.19
0.82	4.07	6.65	8.39
	4/8	8/8	16/8
0.21	1.00	1.61	2.03
0.41	2.05	3.27	4.11
0.82	4.14	6.55	8.18
	6/12	12/12	24/12
0.21	1.03	1.65	1.86
0.41	2.43	3.19	3.78
0.82	4.05	6.38	7.56

3. Measurement Setup

The setup consists of two main parts. The first is the uniform magnetic field generator powered by a sinusoidal signal from wave generator amplified by power amplifier. Second is a spin-valve giant magneto resistance (SV-GMR) probe supplied by an analog bipolar DC power supply. The output signals V_{out} and V_{ref} from bridge of the SV-GMR probe are amplified by the AD524 amplifier and connected to the lock-in amplifier. The amplitude and the phase of the output voltage from the sensor are recorded by the computer connected to the lock-in amplifier by

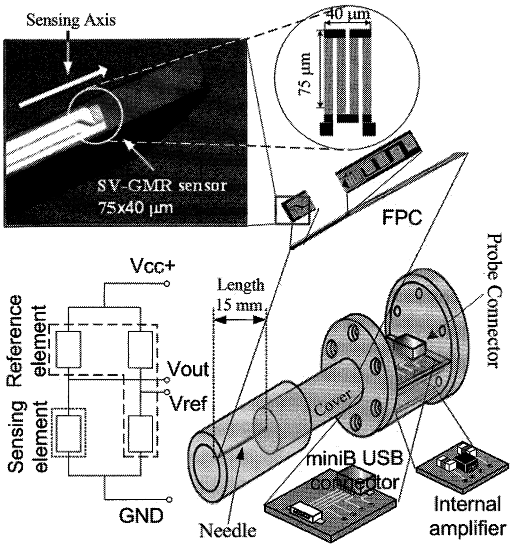

Fig. 3 SV-GMR needle type probe details.

GPIB interface. The uniform magnetic field generator designed according to the analysis of the Lee-Whiting [1] consists of four circular coils. Two external coils have 140 turns each. Middle coils have 62 turns each. The uniformity region at the center of the Lee-Whiting coil is assured up to 8th order. Applied uniform quasi static magnetic field inside the setup is equal to 700 μT with the frequency equal to 100 Hz. The sensing element of a setup has to possess very good spatial resolution and high sensitivity. Both of these features are the main advantages of the SV-GMR needle type sensor. The needle type SV-GMR sensor fabricated by TDK, presented in Fig. 3, was utilized in the measurements. The main part of this sensor is a needle consisting of four GMR sensing elements connected in a Wheatstone bridge. Each sensing element has dimensions of 40 μm x 75 μm. One sensing element is placed at the tip of the needle and three other are located close to the bonding pads. The length of the needle is equal to 2 cm and its cross-section is 250 x 250 μm. The needle sensor is designed to take the signal near to the object of the interest and the reference signal emanating from applied magnetic field. The needle probe has a high sensitivity equal to 11 μV/μT. The sensor measurement range is within tens of nT to few mT. Sensing axis of the sensor is marked in Fig. 3. The Wheatstone bridge connection of the sensor elements provides the ability to measure simultaneously signal from the measured object and the reference signal (see Fig. 1 and 3. The needle with four sensing elements is connected by flexible printing circuit FPC to the printed circuit board PCB with mini-B USB connector. Under the PCB the differential amplifier is connected. The sensor signals V_{out} and V_{ref} are connected to the amplifier. Sensor voltage supply and the differential signal are connected by a mini-B USB cable.

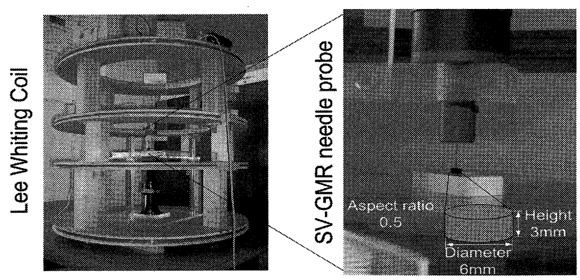

Fig. 4 Sample under examination.

4. Measurement Method

Samples with different dilutions (0.8, 0.4, 0.2, 0.0 %) of the magnetic fluid (dextran magnetite), were prepared in order to examine signal changes. Due to form specified sample shape, magnetic fluid was combined with agar powder. Samples after the night jellification become hard enough to cut them in specified shape. Samples were cut into three aspect ratios (height/diameter) 0.5, 1.0, 2.0 to achieve three different demagnetizing factors. Prepared samples were placed centrally in the Lee Whiting coil with uniform magnetic field 700 μT. The SV-GMR sensor probe was immersed inside the center of the sample. Fig. 4 presents the real picture of the sample under examination. The sensor was placed centrally in the middle of the sample. Differential signal V_{out}-V_{ref} amplified by the AD 524 amplifier was supplied to lock-in amplifier (NF Li5640). The amplitude of the signal was recorded for 10 seconds with interval equal 1 second by a computer connected to the lock-in amplifier. Due to intrinsic noise of the GMR sensor the signal amplitude from 10 seconds was averaged and used as a sensor output. Measurements were repeated at least three times for each sample. Current producing the magnetic field was controlled by the current clamp connected to oscilloscope. The small changes of the current were manually corrected by the change of the wave generator signal amplitude. As a locking amplifier reference signal the wave generator reference signal was exploited. The main possible error source during sample examination is improper sensor placing. The smaller sample dimensions are, the more difficult placement of the sensor in the middle of the sample is. That is why the samples smaller than 6 mm in diameter were not examined.

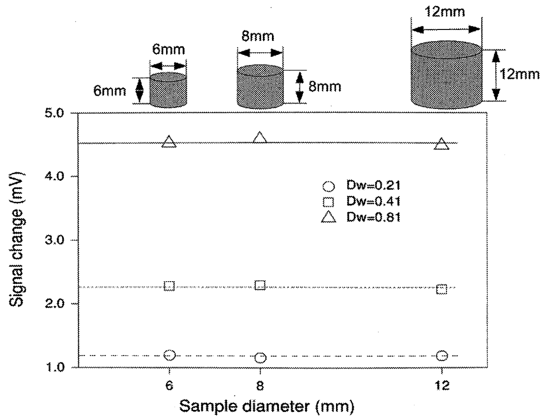

Fig. 5 Size signal dependence, aspect ratio = 1.0.

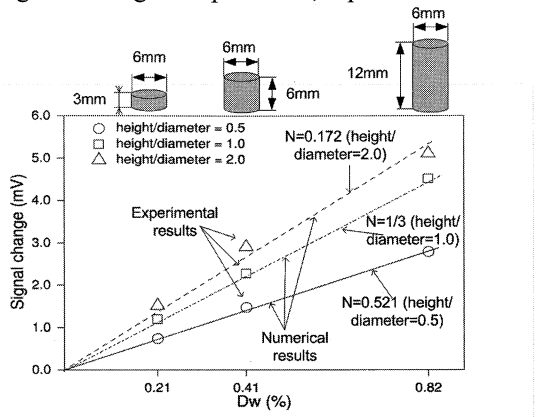

Fig. 6 Aspect ratio signal dependence, (sample diameter = 6mm).

5. Experimental Results

The cylindrical shaped samples with different sizes were examined. In order to produce these samples magnetic substance dextran magnetite (Resovist®) was exploited. Different sizes and shapes were produced with dilution of a specified amount of measured substance in 10 ml of liquid agar. The experimental results of the influence of sample size on the magnetic flux density are presented in the Fig. 5. It can be easily noticed that the sample size has a very small influence on the signal change. This result agrees well with the analytical calculation described in references [1], [5]. Moreover the influence of the aspect ratio is small. In fine diluted samples were D_w is smaller than 0.4 % the signal change is smaller than 1 μT. High sensitivity of the SV-GMR needle type sensor and the extremely uniform magnetic field generator allows us to examine such small changes. The results of the aspect ratio influence on the signal changes are depicted in Fig. 6. Similar results were achieved with samples having diameter 8 mm and 12 mm. The signal change is linearly dependent on the concentration of magnetic fluid D_w. The shape ratio affects signal changes linearly too. It can be noticed that the changes of the signal agree well with the numerical calculations. The magnetic fluid consisting of nanoparticles causes the changes in the externally applied field. The dextran magnetite characteristics were described in [1].

6. Conclusions

The theoretical (numerical) calculations agree well with the measurement results. Linear dependence of the signal change for different dilutions of magnetic fluid allows estimating the magnetic relative permeability of the sample. The high sensitivity of the sensor allows detecting the changes caused by the sample shape ratio. Therefore, the magnetic permeability of the sample can be estimated when the sample size and shape is known. Experiments performed with different aspect ratios of samples showed linear dependence between D_w and change in magnetic flux density. The experimental setup currently utilized had a detection limit around D_w=0.1 %. The possible errors are caused by the sensor placement error, possible noise sources and non-uniformity components of Lee Whiting coil. The extremely high sensitivity of the SV-GMR probe and its amplitude and phase independence from the applied magnetic field frequency change allows utilization of this probe in susceptometry measurements.

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